WELDING RESEARCH

SUPPLEMENT TO THE *WELDING JOURNAL,* JUNE 2006

Sponsored by the American Welding Society and the Welding Research Council

Mechanical Behaviors of Resistance Spot Welds During Pry-Checking Test

BY C. L. TSAI, D. W. DICKINSON, C. Y. KIM, AND M. D. GARNETT

ABSTRACT. The stamping and assembly plants commonly use a wedge or bend pry-checking test to detect stick welds. When this testing method is used on stiff sections, the resulting stress at the edge of the resistance spot weld may unknowingly initiate weld failure. With the increased use of advanced high-strength steels, an increasing number of resistance spot welds run the risk of being damaged during routine pry-check testing. This study conducted a parametric numerical analyses of wedge testing using the virtual modeling and simulation method to investigate the effect of material type, part thickness, wedge prying angle, pitch distance, and weld button size on the checking sensitivity. The purpose of this study is to aid in the development of standards for when pry-checking should be avoided. New knowledge is established to define this weld inspection procedure for the advanced high-strength steels in this study.

Introduction

Quality checks in the operational procedure of resistance spot welding assembly require equipment set-up verification and ongoing quality assurance (Ref. 1). Equipment set-up verification on initial machine set-up is based on peel tests. Set-up verification after major maintenance, set-up changes, or changing steel supplier or steel type, consists of either peel test or non-destructive ultrasonic test. Ongoing quality assurance during production consists of destructive peel testing to determine button size and a visual check of the weld area for discrepancies. Pry-checking is a less destructive test method that permits a reduction in peel test frequency in the production assembly. It may also be used as an aid in equipment set-up verification after major maintenance on the welding equipment.

Pry-checking wedge or bend testing, may be used to detect “stick” welds without a risk of damaging good welds in the production assembly. Excessive deformation in the parts caused by the pry checking is hammered to restore the shape. When the pry checking method is used on stiff sections of higher strength steels, the resulting stress at the edge of the resistance spot weld may unknowingly initiate interfacial failure in otherwise satisfactory welds. With the increased use of advanced high strength steel (AHSS), an increasing number of resistance spot welds run the risk of being damaged under routine pry-check testing. Several hundred welds per vehicle are at risk in production. Procedure standards are needed to determine when pry-checking should be avoided, or proper testing procedures need to be developed to avoid the risk of damaging good welds.

This study investigates the critical variables associated with the pry-check testing to define the inspection procedure for AHSS using the finite element tools. The purpose is to aid in the development of pry-checking test standards. The results enhance understanding of the testing method as to how the test variables affect the mechanical state at the weld nugget and the amount of plastic deformation in the weld joint. Contact pressure between the part and wedge surfaces reflects the weld stress or strain condition during pry-checking. A sudden deviation of the contact pressure behavior from the referenced normal weld joint would indicate detection of "stick weld" or tearing the undersized spot weld in the joint. This paper demonstrates a quantifiable relationship between the contact pressure and the weld stress or strain condition.

Keywords

Resistance Spot Welding
Weld Quality
Pry-Check Test
Finite Element Analysis
High-Strength Steel

Pry Checking Test

Pry-checking test method is analogous to a chisel test. The wedge prying test consists of driving a wedge adjacent to a weld between the welded parts. The bend prying test consists of driving a wedge between the welded parts directly toward a weld, but without actually driving the wedge into the nugget. Figure 1 shows a schematic presentation of the wedge test, which is the focus of this study.

The presence of the wedge establishes a pulling type load at the edge of the weld button. For the analogous destructive chisel testing, some previous studies showed that the chisel test resulted in the most stringent test condition (Refs. 2, 3) and a smaller lobe curve as compared to that generated by the peel test (Refs. 4, 5). Thus, welds in service would be more reliable if the weld schedule is determined based on the chisel test results. The pry-checking test is an alternate to the destructive chisel test for set-up verification in production. The material deformation

---

C. L. TSAI, D. W. DICKINSON, and C. Y. KIM are with The Ohio State University, Columbus, Ohio. M. D. GARNETT is with DaimlerChrysler Corp., Dearborn, Mich.

and stress/strain are limited to a level not causing destruction of good welds and the parts. Hammering is usually used to restore the deformed part shape.

During pry check testing, the material immediately next to the good weld is pulled above the face of the weld to provide a load on the edge of the weld. If the load can be maintained between the two parts prior to breaking an acceptable weld button, then the weld is not discrepant as being a "stick weld" or "undersized". If the load cannot be maintained and the weld breaks prior to pulling the button, a "stick weld" is detected, and the weld is discrepant. If a button pulls without showing excessive deformation in the part material, the button should be at least equal to the required minimum weld size, as specified by the design standards (Ref. 1).

If the weld is undersized, a lower level of wedge load, or contact pressure between the wedge and part surfaces, should be maintained at least for a short wedging distance. For a severely undersized weld button, contact wedge pressure drops when the weld starts to tear. The pry-checking test sensitivity needs to be studied to differentiate the different mechanical behaviors between the joint with a stick weld and the joint with undersized weld.

To date, another technical issue relating to the pry-checking test remains unaddressed. Some of the procedure standards require prior-to-test trials, which require destruction of a few parts, to develop the skill necessary to perform the test. A greater concern in this testing method is that the criteria for a satisfactory pry-checking test are subject to skill-based judgment and the procedure guidelines are nonquantitative. Since AHSS are of higher strength, the uncertainties associated with the pry-check testing may either be incapable of detecting a stick weld, or increase the risk of damaging a good weld during the routing test. Fundamental studies are required to address this technical issue.

Method of Approach

To aid the development of pry-checking test standards, a functional analysis of essential test parameters, which influence the stress/strain state at the edge of the weld and deformation in the parts around the wedge, was conducted in this study. The analysis used a numerical (finite element) procedure conducting virtual test simulations and parametric investigations.

In this study, only the wedge test was studied. The part geometry was defined by its width and length of the test coupon — Fig. 1. Two material types, mild steel and DP600 steel were investigated. A hybrid mild steel/DP600 steel joint was also modeled to determine the effect of strength difference on the wedge load sensitivity.

The constitutive true stress-true strain relations with kinematic work-hardening, postyield behavior were incorporated in the model. To model the stick weld behavior, the constitutive stress-strain relation was assumed to have a small fracture strain (e.g. a brittle behavior). Two part thicknesses, 1.20 mm and 2.03 mm, were modeled to study the effect of part stiffness.

The wedge loading process was simulated by moving a rigid wedge from the edge of the joint inward between the parts and the welds, by which a moving displacement boundary condition is defined. Three wedge or prying angles, 7, 11, and 15 deg were modeled using this displacement-controlled loading process. To study the effect of weld undersize, several smaller than design-required button sizes were modeled using a 11-deg prying angle on a 2.3 mm-thick DP600 steel joint. The effect of pitch distance between two spot welds on the wedge load sensitivity was also investigated. Table 1 summarizes the parametric variations in button size and pitch distance investigated in this study.

In this study, a moving contact interface between the rigid wedge and the part surfaces was simulated. Three types of numerical analysis in the following sequential order were conducted. They are as follows:

1) Develop the baseline information on DP600 steel joint by simulating three in-production test steps including a) prying or loading, b) wedge withdrawal or unloading, and c) hammering to restore the part shape. Equivalent stress, strain and part deformation were predicted for the three simulation steps.

2) Conduct the parametric analysis investigating the effect of a) material model including hybrid joint and weld heterogeneity, b) prying angle, c) weld size, d) stick weld constitutive stress-strain relation, and e) pitch variation.

3) Analyze the relationship between the wedge contact pressure and the weld stress/strain in a normal DP600 steel joint, as well as in two discrepant weld joints, with one containing a stick weld and the other containing two undersized welds.

The numerical analysis determined a) the distribution of the equivalent stresses and strains in the parts, as well as the maximum values at the critical weld location (peak strain location), to study the checking sensitivity; b) the opening displacement distribution of the parts to study the deformation mode; and d) the transient changes in contact area and contact pressure between the wedge and part surfaces during the prying stage to assess the feasibility of an instrumented pry-checking test procedure. The results and discussions are summarized in the following sections.

The Finite Element Model

The finite element model was developed on a numerical platform defined by the commercial finite element analysis (FEA) code *ABAQUS* Version 6.4 (Ref. 6). The analyses were conducted using programs capable of handling nonlinear, elastic-plastic analysis with large deformation, kinematic work hardening material characteristics, and moving contact interfaces between wedge-to-part and part-to-part interfaces. Because of symmetry about the wedge mid-plane, only one half of the test specimen was modeled for the virtual test, except that the weld joint containing a discrepant weld or the hybrid-material model was analyzed using a full-model. Figure 2 shows the half-model and mesh design. The full-model used the same mesh design as used in the half-model with a geometrically symmetric condition along the centerline between the two welds. The unsymmetrical weld condition due to a discrepant weld would result in asymmetric stress-strain fields in the weld joint.

Two element types, 8-node linear brick (C3D8) and 6-node linear triangular prism (C3D6), were used for the part material and the wedge, respectively. Six nodal degree of freedoms, three linear and three rotational, were used in the generation of the element stiffness matrix. The virtual test model was composed of the following mesh designs for 1.20 mm and 2.03 mm part thicknesses (half-model):

- Total number of elements: 7144 (1.20mm part thickness) and 9002 (2.03mm part thickness)
- Total number of nodes: 11187 (1.20 mm part thickness) and 14228 (2.03 mm part thickness)
- Global degree of freedom: 33561 (1.20 mm part thickness) and 39816 (2.03 mm part thickness)

The full-model contained approximately twice the elements, nodes and degree of freedom, minus the respective numbers due to shared boundary elements in the symmetric midsection.

The nodes in the weld button interface area were connected together between the two sheets. The other top/bottom part contact interface and the part/wedge contact interface were established using the *ABAQUS* command CONTACT PAIR to define master surface and slave surface, and using the grouping commands ELSET and SURFACE to define the contact pair groups. At the wedge-to-part interface, the moving contact condition was established by a user interfacing command defining the transient contact area as the wedge moving into the joint. The peripheral edges around the virtual test model were free, except along the mid-plane of the half-model where a symmetry condition was assigned.

Figures 3A and B show the respective true stress-strain curves for mild steel (Ref. 7) and DP 600 steel (Ref. 8). The initial high rate of work hardening associated with the DP 600 steel is commonly observed in the material's tensile test. In addition, DP 600 steel has higher tensile-to-yield ratio than mild steel. The finite element model incorporated the respective constitutive relationships and the characteristic behaviors of the two steels. The prying wedge was assumed to be a perfect rigid body.

In order to study the effect of heterogeneity induced by welding, Fig. 3A and B also show assumed changes in the constitutive relation due to welding. Microhardness of resistance spot welds in DP600 steel was reported showing more than 50% increase in the weld and HAZ from the base steel (Ref. 9). In this study, it assumed that both weld metal and heat-affected zone (HAZ) have greater yield and tensile strengths than the base metal due to fast cooling effect. It also assumed that the weld metal and HAZ would reduce their ductility due to embrittlement. The HAZ was assumed to be 1 mm wide for all cases studied.

For the full-model containing a stick weld, it was assumed that the stick weld broke when weld stress or strain went just beyond the yield point. Figure 4 shows the hypothetical true stress-true strain behavior of the stick weld in DP600 steel joint. For undersized weld button, the stress-strain curve for the normal weld, which is also shown in the same figure, was used in the analysis.

Results and Discussion

During pry-checking test, the wedge is driven into the joint and pulls the joint materials apart resulting in high stress and strain condition on the edge of the weld button. Significant amount of yielding on the weld edge is anticipated to occur when the tip of the wedge approaches the weld centerline section (i.e. mid of the test specimen). The weld starts to tear when the strain reaches the ductility limit of the part material, the weld, or the HAZ in accordance with the respective constitutive relations. A proper pry-checking test should show breaking of the stick weld with a sudden relaxation of the wedge load. For joint containing undersized welds in high-strength and thick steel, tearing occurs in weld HAZ when the strain reaches material's fracture strain under or at the limiting wedge load, which is specified in the operating procedure not to damage the good weld.

For mild steel joint, or high strength steel joint with smaller thickness, excessive deformation in the part material may be shown in lieu of tearing the weld button. For welds equal to or greater than the minimum acceptable button size, tearing should not occur, the part deformation should be smaller, and the wedge load should be maintained. The contact pressure at the wedge and part interface reflects the magnitude of the wedge load and the state of stress/strain at the weld edge.

A quantifiable correlation between the state of maximum stress or strain at the weld edge and the wedge load or pressure for a given weld joint condition provides information on the checking sensitivity and the effectiveness of the pry-checking design. This correlation should be a function of material's mechanical properties including yield/tensile strength and the work hardening behavior, joint stiffness or part thickness, prying angle, and the pitch distance between weld buttons.

Another issue besides the stress or strain in the pry-checking test is the part deformation. Because of large opening (tensile) plastic strains at the weld edge and the plastic strains extended to the areas around the wedge and other areas in the joint, the weld joint remains open after wedge withdrawal. The spring back in the part material is insignificant due to the overwhelming plastic strains. Hammering on the deformed joint is usually necessary to restore its shape. However, excessive plastic deformation should always be avoided by proper test procedure design. The following sections summarize the primary results obtained from the numerical study.

Virtual Test Simulations

Figure 5A through C show the maps of Von Mises equivalent stresses in the deformed weld joints at end of the prying stage for DP600 steel of 2.03 mm part thickness using three respective prying angles, 7, 11, and 15 deg. The minimum required weld button size for the DP600 steel joint having 2.03 mm thickness is 6 mm per Chrysler's draft process standard (Ref. 1). The gray color shows area without yielding. The other colors show the areas where yielding has occurred at different stress magnitudes during the prying process. The maximum stress is at the weld edge approximately in the 7 o'clock position. As the prying angle increases, the opening displacement increases. The maximum stress area also expands due to increasing prying angle. Similar results are observed for 1.20 mm joint with a minimum required button size of 4.5 mm (Ref. 1) (Fig. 5D through F). The maximum stress at weld edge in the 1.20 mm joint is at the 6.5 o'clock position. When the results are compared between two thicknesses with the same prying angle, thicker joint shows higher stress magnitude and opening displacement.

For mild steel joints, the effects of prying angle and part thickness have similar trend to the DP600 steel joints. However, due to lower yield strength of the material, the plastic zone spreads more extensively and the opening displacement is slightly greater in the mild steel joints. Figures 5G through H show the effect of prying angle on 2.03 mm mild steel joints. Joint with 7-deg prying angle is not shown in the figure due to excessive yielding in the part material, which resulted in button pull-out failure mode. Figure 5I through K show the effect of prying angle on 1.20 mm mild steel joints. Thicker joints show higher stresses and greater displacements. Only those areas, where yielding has occurred, show color stresses.

For a hybrid joint composed of mild steel and DP600 sheet, the analysis shows that the stress magnitude is reduced in DP600 steel, but stress is increased in mild steel. Mild steel deforms more than DP600 steel causing the joint to bend asymmetrically about the original interfacial plane between the two materials. The bend angles at the weld edge are 5.54 and 6.16 deg in DP600 steel and mild steel, respectively — Fig. 6. This observation may be explained by the effect of changing the stiffness due to amount of yielding in part materials. With less stiff (e.g. greater yield zone) mild steel, part deformation is greater. Deformation in DP600 steel is smaller due to smaller yield zone. Although the stresses in mild steel are lower than that in DP600 steel, the stress magnitude is actually increased in mild steel, but decreased in DP600 steel, in comparison with the homogeneous joints, due to decrease or increase in stiffness of the counterpart material. This observation is shown by two orange colored stress planes plotted versus the respective stress bars in Fig. 7.

When welding DP600 steel and mild steel together, the carbon dilution may occur and it could change the weld failure mode. The button pull-out failure mode in mild steel may change to "interfacial" failure mode. This metallurgical effect would cause the hybrid joint behaving like the DP600 steel joint. This phenomenon may be incorporated in the FEA model by modifying the stress-strain relations for the weld and HAZ. In this study, no such metallurgical reaction was considered.

Figure 7 summarizes the maximum

Von Mises equivalent stresses of 12 parametric cases using bar charts. The equivalent stresses are normalized by the respective yield strength of mild and DP600 steels. The normalized tensile strength of both materials is also shown in the same figure. The only case showing tearing failure (i.e. when the calculated maximum stress is greater than material's tensile strength) is the DP600 steel joint of 2.03mm thickness with a 15-deg prying angle. All other cases show the stress magnitude near, or below the respective tensile strength. A generic observation from Fig. 7 demonstrates four mechanical behaviors of the weld joints during the pry-checking test:

1) The joint stiffness (part thickness) and the prying angle both increase the stresses and deformation in the joint.

2) Stress at weld edge is greater in the high strength steel joint for the same part thickness and prying angle. Stress is also higher in the thicker joint of the same material. The maximum equivalent stresses are much closer to material's tensile strength in DP600 steel. Due to smaller ductility of DP600 steel, weld tearing was predicted for 2.03mm-thick joint using 15-deg prying angle.

3) Although the normalized stresses, as shown in Fig. 7, look higher in mild steel, the maximum equivalent stresses are much below its tensile strength. Due to greater material's ductility, the spot weld in the mild steel joint does not tear under the parametric conditions studied. The weld button is expected to be pulled out due to excessive yielding in the weld and its surroundings when a wedge with large prying angle is used.

4) For the hybrid joint model, stress is decreased in the high strength part, but is increased in the low strength part. The two orange colored stress planes shown in Fig. 7 indicate the stress magnitude in the respective parts. Only one case simulating 2.03 mm part thickness and 11 deg prying angle was studied.

To illustrate the mechanical behaviors of the spot weld joint under a complete three-stage loading cycle (i.e. prying, wedge withdrawal, and hammering) of the pry-checking test, a virtual test simulation was conducted to show the stresses and deformations at each stage for DP600 steel, 2.03 mm thickness, and 11 deg prying angle. Figure 8A through C shows the respective state of stresses and deformations at end of the prying stage, after removing the wedge, and after applying and removing a uniform pressure of yield magnitude to and from the entire deformed joint surface (i.e. hammering model assumed uniform pressing in lieu of dynamic hammer blowing).

Upon withdrawing the wedge, spring back is insignificant due to high magnitude of plastic strains created by the prying process. Almost all plastic strains transform into total strains, which are shown in opening displacements. The residual stress is only limited to the weld nugget and its surroundings.

After pressing the joint surfaces by uniform pressure of yield magnitude, the joint restores to its flat shape, however, the cumulative plastic strains result in compressive residual stresses quite extensively in the joint as shown in Fig. 8c. The distribution of the residual stresses is rather uniform in most of the parts. Very high stress magnitude (red color) is shown in the weld zone. The significance of these compressive residual stresses on weld performance is subject to future study.

Figures 9a and 9b show strain changes at the critical weld edge in the respective mild steel and DP600 steel joints, as the wedge being driven into the joint. The strain-wedge displacement relationship suggests a correlation between the joint opening displacement and the load on weld. Depending upon the joint stiffness due to part thickness and yield zone size, the weld load can also be correlated to the wedge load or the contact pressure at the part/wedge interface. Understanding of the sensitivity of the weld/wedge load correlation will help in the development of the pry-checking test procedure.

The strains are normalized by the yield strain ($_{eq}$/ $_{Y}$) of the respective material. The wedging distance is normalized by the part thickness (D/t). The yield line and the tensile strength line are also plotted in the figures for comparison purpose, except that the tensile strength line for mild steel is outside the plot range and not shown in the figure. Each strain-to-wedge travel distance curve is labeled in the format as: part thickness_prying angle_percent button size reduction. Those curves without percent button size reduction in the label are joints having standard button size required by the design specification (e.g. 6.0 mm for 2.03 mm joint and 4.5 mm for 1.20 mm joint).

In all cases studied, yielding starts shortly after the wedge moves inwards. The plastic flow in the thin joint is slower than that in the thick joint. It accelerates when the wedge travels to a distance approximately 10 times the joint thickness for DP-2.03 mm. For the thin joint (DP-1.20 mm), the plastic flow starts to accelerate when the wedge travels to a distance approximately 18 times the joint thickness. The strain magnitude in the DP600 steel joint with 2.03-mm part thickness and 15 deg prying angle is higher than the tensile strain, which indicates tearing of the weld.

The state of strain in the hybrid joint and the joint with reduced weld button size are also shown in Fig. 9. For the hybrid joint (MS/DP-2.03 mm-11 deg), the strain magnitude is increased by approximately 40% (Fig. 9A) in mild steel. However, it is reduced by approximately 50% in DP600 steel — Fig. 9B. The results showing the effect of reduced weld button size (e.g. curves showing a percentage value in its label) will be discussed in the latter section.

The strain plots present the same observations from the stress results on the effect of material type, part thickness, and prying angle as shown in Fig. 7. However, the strain plots show higher sensitivity to the testing parameters than the stress plots due to the inherent characteristics of the stress-strain relationship in the region with large plastic flow. The dot on top of each strain curve shows the strain magnitude after wedge removal, which remains practically unchanged from the prying stage, demonstrating small strain relaxation.

Effect of Prying Angle

To further demonstrate the prying angle effect on the stress condition at the critical weld edge, Fig. 10 plots the maximum equivalent stresses directly vs. the prying angle. The stresses increase with the prying angle almost linearly. This is due to the displacement controlled loading situation associated with the wedge test. This observation shows the possibility of predicting the effect of prying angle using a linear model for the wedge prying test design.

Figure 10 also shows two dot points labeled as MS/DP and MS/DP, respectively, indicating change of stress magnitudes in the hybrid model. The stress is reduced in DP600 steel, but increased in mild steel. The dot point labeled as MS/DP shows the stress magnitude in mild steel. The dot point labeled as MS/DP shows the stress magnitude in DP steel. In the same figure, the effect of weld size is also shown by the dots labeled with a percentage reduction value. This effect is discussed in the next section.

Effect of Button Size

To study the effect of weld undersize on the test sensitivity in detecting stick weld using the wedge prying test, a full FEA model was used to accommodate the effect of weld size reduction. Without changing the weld center location, the undersized weld button was reduced from its standard required minimum size by 20, 40, 50, and 60%. DP600 steel joint with 2.03-mm part thickness and 11-deg prying angle was the only case investigated for the weld size effect.

The maximum stress results from the analysis of the undersized weld joint are shown by the four dots labeled with the reduction percentage value in Fig. 10. The maximum stress and strain values are also plotted vs. the percent button-size reduction in Fig. 11A and B, respectively. All plots show an increase in stress or strain for size reduction up to 40%. For further size reduction, the increasing trend levels off and then decreases. Although the plots show weld tearing at 40% size reduction, it suggests insensitivity of the pry-checking test in detecting very small welds. Therefore, the wedge pry-checking test may have limited sensitivity window for a specific test procedure, which makes the test procedure nonunique for detecting undersized welds.

To explain the behavior of undersized welds, a theoretical model (elastic) analogous to beam bending was developed — Fig. 12. The four simple supports simulate the weld edges restraining the beam from vertical displacement due to push-down (opening) displacement in the middle of the beam. When a weld size ( ) is reduced, the pitch distance ( ) is increased by half of its button diameter change (d/2). Since the wedge pulls open the weld button creating a tearing load, the section property of the weld resisting such pulling load is the section modulus (S) of the faying surface area of the weld. This section modulus reduces (S) as the weld size reduces (d). For a given opening displacement value at the wedge, variations in the maximum bending moment (M/M), the section modulus (S/S), and the maximum bending stress (/) at the weld edge, or support in the beam model, can be derived and summarized as

$$\frac{\Delta M}{M}=\frac{1+\frac{2}{3}\frac{d}{\,}}{\left(1+\frac{\Delta d}{2}\right)^{2}\left(1+\frac{2}{3}\frac{d}{\,}\frac{1-\frac{\Delta d}{d}}{1+\frac{\Delta d}{2}}\right)}-1 \qquad (1)$$

$$\frac{\Delta S}{S}=\left(1-\frac{\Delta d}{d}\right)-1 \qquad (2)$$

$$\frac{\;}{\;}=\frac{\frac{M}{M}+1}{\frac{S}{S}+1}\quad 1 \qquad (3)$$

By variation of the button size (d) without changing the loading displacement, the section modulus variation of weld button, and the bending moment and stress at weld edge are plotted in Fig. 13. The moment variation (M) increases with the size reduction. It also increases with the initial button size-to-pitch ratio (d/). Because of the significant decrease in the section modulus variation as the button size reduces, the stress variation is not sensitive to the size-to-pitch ratio. The rate of stress increase starts to grow at about 40% size reduction and becomes very fast when the size reduction is beyond 60%.

This theoretical model explains the initial stress or strain-button size behavior as shown in Fig. 11A or B, respectively. Up to 20% size reduction, the stress or strain remains unchanged. The stress or strain increases when the button is reduced by 20% to 40%. Beyond 40% reduction, the theoretical model no longer predicts the simulated wedge pry-checking test behavior.

By examining the deformation mode of the simulation results with different button sizes, it shows a change in deformation mode when the button size reduction is beyond 40%. The part material bends about an axis connecting the two weld centers, which bulges up the part material leaving it noncontact with the wedge surface at the wedge tip, which increases the stress magnitude in that region. This results in an expanded plastic zone towards the wedge — Fig. 14.

Figure 15 plots a series of vertical displacement curves in the wedging direction (in W-direction) across the width (in L-direction) of the weld joint. For the normal weld button size (band of blue curves showing 0% reduction), the part material is in complete contact with the wedge surface. For the joint having an undersized weld with 60% button reduction (band of red curves), the part surface bulges above the wedge surface at the wedge tip and its surroundings. The narrower red displacement band indicates a rotational deformation mode in the part material.

When the deformation mode is changed from bending to bending/rotation for smaller welds, it actually relaxes the weld load by shifting the moment away from the weld. This explains the downturn behavior in the stress or strain vs. button size curves — Fig. 11.

Effect of Heterogeneous Material Properties

It is well understood that welding causes changes to the metallurgical structures in the materials. The weld metal and the HAZ may become stronger or weaker than the base metal depending upon material chemistry and the material's heat treatment condition prior to welding. Resistance spot welding mild steel, the weld metal and HAZ are usually becoming stronger, but less ductile. For the dual-phase, high strength steels, the consequence of resistance spot welding on the metallurgical evolution in the weldment may be significant due to the unique work hardening characteristics of the material. To date, efforts have been made by researchers to generate the resistance welding data addressing this metallurgical issue. Microhardness traverse across the weld is commonly measured to show the metallurgical effect (Ref. 9).

To demonstrate the numerical capability of the virtual test model in analyzing the effect of this heterogeneity condition in the resistance spot weld, the hypothetical constitutive relationships for the weld metal and the HAZ in both mild steel and DP600 steel were assumed (Fig. 3A and B). The size of HAZ was approximated from the available experimental data (1 mm). The tensile strength was assumed to be increased by 15 and 30% in the weld metal and HAZ, respectively, from the base metal strength. The ductility was assumed to be reduced by 25 and 50% in the weld metal and HAZ, respectively, from the base metal ductility. The yield strength was also assumed to be increased in the weld metal and HAZ.

The numerical analysis was conducted on both material types (mild steel and DP600 steel) with 2.03-mm part thickness and 11o prying angle. Figures 16a and 16b show the strain changes in the three metallurgical zones as the wedge moves into the joint. The curves shown are at the maximum stress/strain location in each metallurgical zone. The strain curves obtained from the previous analysis with homogeneous material property are also shown in the respective figures. The dots show the strain values after complete wedge withdrawal from the joint. Very little spring back is seen due to large plastic deformations in the joint induced by the prying process. The constant ductility lines normalized by the material's tensile strength are presented in the same figures for various metallurgical zones. The calculated maximum strains are compared with the material's ductility for weld failure assessment.

Figure 16 shows similar trends for both material types. The strain growth rate increases drastically when the wedge is driven close to the weld centerline (the line connecting two weld centers). The wedge load does not move into the weld button, which results in very little strain increase in the weld metal. The stronger weld metal and HAZ drive up the stain magnitude in the base metal as compared to the predicted results using the homogeneous material properties. Although the strain magnitude is lower in the HAZ than that in the base metal, because of the significant HAZ embrittlement due to welding, weld tearing is predicted in the HAZ of DP600 steel weld.

For mild steel weld, should weld failure occur due to excessive wedge pulling, it would happen in the base metal next to HAZ. This hypothetical analysis predicted different weld failure mechanisms: tearing in the HAZ for DP600 steel weld and button pull-out in the base metal next to the HAZ for mild steel weld. The analysis results demonstrate that special care must be exercised when pry-checking the DP600 steel weld if welding causes brittle HAZ.

Effect of Pitch Variation

For a given prying angle, increasing pitch distance between welds would reduce the weld load, hence, reduces the maximum stress or maximum strain on the weld edge. The analysis was conducted on both mild steel and DP600 steel with 2.03-mm part thickness and 11-deg prying angle. Figure 17 shows the maximum equivalent strain variations with the pitch distance for mild steel and DP600 steel joints. The results show that mild steel is less sensitive to the pitch effect than DP600 steel. However, when the pitch distances are smaller than the threshold value (40 mm), the strains increase rapidly in both materials. The strain magnitude becomes higher than material's ductility in DP600 steel when the pitch distance is less than 25 mm. The influence of pitch distance is more significant in DP600 steel.

Contact Area and Contact Pressure

As the wedge drives into the joint, the contact area between the wedge and part material interface moves backwards from the wedge tip towards wedge base. Contact pressure at the interface builds up in the contact surface at faster rate when the wedge tip is near the weld centerline. When the stick weld breaks or the undersized weld starts to tear under the wedge load, sudden load or pressure relaxation is anticipated. In this study, a preliminary analysis on contact area and contact pressure for both mild steel and DP600 steel with 2.03-mm part thickness and 11-deg prying angle was conducted. The brittle behavior of the stick weld was only considered in the DP600 weld analysis.

Figures 18 through 21 summarize the analysis results. Figure 18 shows the contact area location and the contact pressure distribution at four wedge tip positions for both materials. The dashed rectangle indicates half of the wedge with a symmetric plane on the left-hand side. The colored area shows contact area and contact pressure with the gray color having the highest magnitude. When the normalized wedging distance (D/t) reaches 12.50, the wedge tip has reached to the midline of the joint.

The peak contact pressure occurs at the edge of the wedge near its tip when the wedge tip reaches the joint midline. The contact pressure change correlates well with the stress/strain history on the weld edge. The contact pressure starts with small magnitude and slow growth rate, but it builds up at faster rate when the wedge tip is near the joint midline.

Figure 19 shows the contact pressure change at three locations (i.e. 2, 5, and 7 mm from wedge tip) on the wedge surface for pry-checking a DP600 steel joint of 2.03-mm thickness with 11-deg prying angle. The contact pressure changes (right vertical axis) and the stress evolution (left vertical axis) in the weld joint are plotted against the wedging distance (D/t) in the same figure. The single solid curve in black color shows the stress behavior for the homogeneous weld joint and the dotted curves show the stress behaviors in the base metal, HAZ and weld button, respectively. The respective strengths (UTS) are also plotted in the same figure. At each monitoring location, the contact pressure builds up to reach a plateau, drops from this plateau, and then vanishes at the respective wedging positions (D/t). This phenomenon is due to bulging of the elastic part material. The contact area moves away from the wedge tip as the wedge drives into the joint. However, when the wedge travels a greater distance into the joint (D/t>11), weld starts to tear in the HAZ and the plasticity spreads from the weld area to the part material around the wedge contact, the elastic bending stress relaxes. The contact area quickly moves back towards the wedge tip. The contact pressure increases rapidly at all three monitoring locations with the maximum near the wedge tip (point 1).

Figure 20 shows 3-D views of wedge location, contact area (red color) at the contact part interface, and plastic strain (red color) in the part material, at seven D/t wedging distances (i.e. 0.82, 2.81, 6.56, 9.38, 10.70, 12.30 and 12.50). These plots support the aforementioned pressure change observations.

With the pressure relaxation and fast rebuilding behaviors at the monitoring locations (shown by the green dots on the wedge contact surface), which correlate to the plasticity redistribution behavior in the part material, the contact pressure evolutions may provide quantifiable information on the weld stress/strain condition at the incipient of weld tearing.

Figure 21 shows weld stress evolutions of a normal weld joint and a deficient weld joint containing a stick weld in the DP600 steel joints with different part thicknesses (2.03mm and 1.20mm). The prying angle used in the analysis is 11o. The curves without prefix in the label show the stress behavior of the normal weld joint (e.g. both welds being good).

For the joint with a stick weld, two stress curves are plotted to represent the stress changes in the normal weld (labeled with a G prefix) and the stick weld (labeled with a S prefix), respectively. The "stick weld" condition does not significantly alter the stress in normal weld, but it shows a significant stress deviation in the stick weld at the failure incipient point due to the assumed brittle behavior of the stick weld — Fig. 4. The wedge pressure drop phenomenon is a reflection of the stress deviation behavior. Figure 22 shows similar observations in the strain evolutions. However, the deviation behavior does not show abrupt strain relaxation as shown in the stress evolution curves.

Figure 23 shows the contact pressure changes at the three monitoring locations in the wedge contact surface, labeled with a circled number. The contact pressure at those locations on the stick weld side of the joint is approximately 400 Pa smaller than the pressure magnitudes on the normal weld side (see the enlarged pressure curves in the plateau area). This difference is significantly small comparing to the magnitude of contact pressure, and hence hardly noticeable in the figure. However, the 400-Pa pressure difference at the pressure plateau between the sides of the wedge contact surface may be monitored using a micro pressure sensor embedded in the wedge to detect stick weld. An instrumented pry-checking tool may be developed based on this concept.

Another observation regarding the contact pressure evolution curves is that a location on the wedge edge 7 mm from the wedge tip shows a pressure plateau corresponding to the beginning of fast flow stress increase in the normal weld. It is believed that monitoring the pressure changes at this location on both sides of the wedge would enable the inspection to detect stick weld without damaging the normal weld, or causing excessive plasticity in the joint.

Conclusions and Continuing Efforts

Conclusions

This study conducted FEA parametric analysis on wedge pry-checking test for detecting stick weld in the resistance spot weld joint. The virtual testing model was capable of simulating the prying process, the wedge withdrawing process, and the deforming (hammering) process. The predicted results showed consistent and rational trends in the effect of material type, part thickness, prying angle, button size, and pitch variation on the critical weld stress/strain condition in the joint. Several observations of the analysis results are significant in contributing to either verifying the existing knowledge, or generating new knowledge to aid in the development of the procedure standard for detecting stick weld without the risk of damaging good weld during routing wedge pry-checking test. These observations are summarized as follows:

1) The critical location in the joint during the wedge pry-checking test is on the weld edge in approximately 6 to 7 o'clock position. When heterogeneous constitutive relationships are considered due to metallurgical structure variations, the critical location is pushed towards the HAZ/base metal boundary in the same o'clock position.

2) The critical stress/strain starts to build up at fast rate when the wedge is driven into the joint over a threshold distance. For stiff joint (high strength material and/or thick joint), this threshold distance is shorter. For soft joint, such as mild steel and 1.20-mm part thickness, the fast growing critical stress/strain occurs when the wedge tip is near the joint midline (line connecting two welds).

3) The critical stress/strain condition is greatly dependent upon the prying angle. Too big the prying angle causes the risk of damaging good welds. Too small the prying angle becomes insensitive to detect stick welds or small welds. 11o prying angle appears to be adequate for the parametric situations investigated in this study.

4) Because of the unique large plastic deformation in the test joint, the parametric effects are more sensitive to strain variations during the wedge pry-checking test. Therefore, strain should be used for the pry checking sensitivity evaluations.

5) The critical stress/strain state increases as weld size reduces. However, this trend is reversed when weld size reduction is beyond the threshold value. For example, wedge pry-checking test of DP600 steel joint of 2.03-mm thickness using 11o prying angle, 40% size reduction from 6-mm button size constitutes this threshold state. Test joint deformation changes from bending mode to a mixed mode of bending and rotation, which reduces the stress/strain magnitude in the weld. Shifting the wedge load away from weld to the part material actually relaxes the weld load. This phenomenon may become a potential problem for wedge pry-checking test to screen the effect of undersized welds on "stick weld" checking sensitivity.

6) The critical stress/strain is higher in stiff joint and in the joint with shorter pitch distance. Sensitivity to the pitch distance may be significant to make the wedge pry-checking test nonunique for generic practical applications. The distance between the wedge edge and the weld edge may have to be specified in the recommended standard test procedure.

7) When the wedge is driven into the joint, the wedge is initially in contact with the joint material along the wedge tip. This contact surface moves backward towards the wedge base as the wedge moves forward into the joint. Because of the joint rigidity, only part of the wedge surface is in contact with the joint material. During the initial wedging process, very little contact pressure is generated in the contact area because the wedge opening displacement has not created sufficient weld load to pull the weld. When the weld load actually builds up, the contact pressure also builds up in the contact area. The analysis results show a correlation between the contact pressure and the weld stress/strain status. This observation suggests a potential use of instrumented wedge for the pry-checking test.

Continuing Efforts

There are several situations not considered in this study that may have significant influence on the wedge pry-checking test when used to detect stick welds. The test model studied assumes free constraint beyond the test weld. However, for pry-checking of production weld assembly, weld next to the test weld may impose certain constraints that would reduce the weld load and hence weld stress/strain. Larger prying angle may have to be used to detect stick weld under this circumstance. To accommodate this situation, multiple-weld or constrained wedge test (at least four welds), or constrained bend pry-checking test needs to be simulated and analyzed.

The wedge pry-checking test is sensitive to many joint variables such as pitch distance and joint stiffness. In addition, the weld load relaxation phenomenon due to change in joint deformation mode associated with small weld may cause additional sensitivity problem for the wedge pry-checking test. Therefore, bend test as an alternative for pry checking needs to be studied. Although bend test can damage good welds more easily than wedge test, its sensitivity to pitch distance and weld deformation mode change would be eliminated. With proper operational procedure guidance and test standards, the risk of damaging good weld can be minimized in bend pry-checking test.

The current study shows evidence of correlation between the contact pressure and the critical weld load during the wedge pry-checking test. Development of an instrumented wedge may provide a new means to quantify the pry checking process. When weld breaks or tears apart the weld load relaxes, which causes relaxation of contact pressure on the wedge. Using the pressure sensor embedded in the wedge is an idea to monitor the contact pressure changes. This new concept needs to be further verified in the future study.

Acknowledgments

This study is a part of the 2004 summer intern professors program sponsored by Doug Gouin and Robert Barstead at the DaimlerChrysler Corporation. Authors acknowledge the opportunity to participate in this program. Permission to publish the results is gratefully acknowledged.

References

1. Draft, DaimlerChrysler Corp. Process Standard. 2004. Resistance Spot Welding Automotive Components and Assemblies Including Advanced High Strength Steels.

2. Funk, E. R. 1954. The significance of the tension test for spot welds. *Welding Journal* 33(7): 363-s to 365-s.

3. Kraus, W. P. 1961. A practical design approach to resistance weld peeling loads. *Welding Journal* 40(10): 1045–1050

4. Dickinson, D. W., Haser, J. M., Ries, G. D. 1974. Lobe Curve Evaluation of the Spot Weldability of MASI-FORM 50 and MASI-FORM 80 Steels. Republic Steel Research Report

5. Sawhill, J. M., Jr., and Baker, J. C. 1981. Spot Weldability Tests for High Strength Steels. SAE Paper No. 810352

6. *ABAQUS* Version 6.4, ABAQUS, Inc., Pawtucket, R.I.

7. Brockenbrough, L., and Johnston, B. G. 1981. USS Steel design manual. As published in *Structural Alloys Handbook*, Vol. 3, CINDAS, Purdue University, 1994, p. 5

8. *Automotive Steel Design Manual*, Section 2.5. 2002. p. 2.1-1 and Fig. 3 at *http://ussaautomotive.com/auto/tech/grades/dual_ten.htm*

9. Marya, M., and Gayden X., Q. 2005. Development of requirements for resistance spot welding dual-phase (DP600) steels: part 1-the causes of interfacial fracture. *Welding Journal* 84(11): 172-s to 182-s

Fig. 1 — Isoperimetric view of part geometry (wedge base height, H varies with prying angle).

Fig. 2 — Finite element mesh design of wedge test (half model).

Fig. 3 — Hypothetical true stress vs. true strain curves for three metallurgical zones: base metal, weld metal and heat-affected-zone (HAZ). A — Mild steel weld; B — DP600 steel weld.

Fig. 4 — Hypothetical true stress vs. true strain curves for brittle weld behavior as compared to normal weld behavior in DP600 steel weld.

Fig. 5 — Von Mises equivalent stress map for DP600 and mild steel welds.

Fig. 6 — Asymmetric bending and Von Mises equivalent stress map in hybrid mild/DP600 steel joint

Fig. 7 — Comparison of maximum Von Mises equivalent stress for 12 cases (variables material type, part thickness and prying angle; yellow color shows stresses in mild steel and DP steel for hybrid joint)

Fig. 8 — Von Mises equivalent stress map under a complete three-stage loading cycle. A — End of prying process; color contours show prying stresses; B — end of wedge withdrawal process; color contours show residual stresses; C — end of hammering process; color contours show final residual stresses.

Fig. 9 — Normalized equivalent strain versus wedge travel distance curves. A — mild; B — DP600 steel joints.

Fig. 10 — Maximum equivalent stresses vs. prying angle (Fig. also shows effect of weld size reduction and hybrid spot weld).

Fig. 11 — Von Mises equivalent stress and equivalent strain vs. % nugget reduction

Fig. 12 — Beam model describing bending load on weld button due to wedge displacement ( ) at the beam center.

Fig. 13 — Variations of bending moments, weld section modulus and weld stress.

Fig. 14 — Von Mises equivalent stress contour on faying surface vs. % weld size reduction (DP steel, 2.03-mm part thickness and 11°-deg prying angle).

Fig. 15 — Change of deformation mode at 60% weld size reduction.

Fig. 16 — $_{eq}/\,_{Y}$ vs. D/t in homogeneous and nonhomogeneous models

Fig. 17 — Effect of pitch distance on weld strain (2.03-mm part thickness with 11-deg prying angle).

Fig. 18 — Contact area and contact pressure at four wedge positions (DP600 and mild steels).

Fig. 19 — Contact pressure evolution at edge locations 2, 5, and 7 mm from the wedge tip as wedge drives into the joint (D/t). Weld stress evolution behaviors are also plotted to show the corresponding pressure changes (DP600 steel of 2.03-mm thickness with 11-deg prying angle)

Fig. 20 — Wedge position, contact pressure (red color) and plasticity area (red color) at seven D/t moments: 0.82, 2.81, 6.56, 9.38, 10.70, 12.30 and 12.50 (DP600 steel of 2.03-mm thickness with 11-deg prying angle).

Fig. 21 — Normalized Von Mises equivalent stress evolutions at normal and stick welds for DP600 steel of 1.20mm and 2.03-mm thicknesses with 11-deg prying angle.

Fig. 22 — Normalized equivalent strain evolutions at normal and stick welds for DP600 steel of 1.20- and 2.03-mm thicknesses with 11-deg prying angle.

Fig. 23 — Contact pressure evolutions at edge locations: 2, 5, and 7 mm form wedge tip on normal and stick weld sides of the joint (DP600 steel of 2.03-mm thickness with 11-deg prying angle).